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Wireless Instrumented Sphere For Three-Dimensional Force Sensing

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***Abstract*— In this work, a spherical shape portable data acquisition system capable of sensing compression and impact forces along the three Cartesian axes is presented. The developed instrument was validated in several different experiments of fruit packinghouses during the post harvest process in order to check the mechanical damages they suffer. It is a microcontroller embedded system that acquires data from four sensors (accelerometers, load cells, temperature and humidity). A Flash memory is used for data storage and a radio frequency transceiver and a universal serial bus (USB) communication port are provided to allow interface with external computers for data-processing and visualization. The case studies indicated strong compression and impact forces suggesting a need for changes in the mechanical and manual selection, packing and transportation of fruits. The developed device was proven to be useful, working as expected and its modular design allows future modifications. The preliminary results obtained with the instrumented sphere point to the need to more concern on damages fruits and vegetables endure along the post harvest handling chain.**

Keywords; Portable Data Acquisition Systems, Data Loggers, Load Cells, Accelerometers.

I. Introduction

One of the areas benefited with latest advances of electronics is the precision agriculture. Several techniques are being used with the intent to maximize food production and the reduction of waste that occurs during the different stages of the agricultural process, from harvest up to the delivery to the consumers. Fruit and vegetable losses that occur in the post harvest are related to a diversity of different factors such as decay, senescence or visual and internal quality losses. In many cases the primary causes are mechanical damages. When those impacts and compressions are not properly taken into account they may lead to the establishment of bacteria and fungi; being these last then considered as the primary cause. This deduction leads to the recommendation of treatments with fungicides in order to diminish the losses. Pesticide treatments are facing restrictions by the customers and its indiscriminate use results in reduction of its efficiency, especially after the upsurge of resistant species of pathogens [1]. So, to combat the primary causes is an effective form to diminish the loss problem. In order to quantify the impacts and compressions forces (the primary causes), electronic devices were and are being developed [2]. Losses estimates vary according to the country and type of vegetable or fruit and in Brazil (one of the major agricultural countries in the world), these losses can surpass 20% along the post harvest handling chain [3] and these are losses without any utility. There are other types of losses that result in bad quality of fruits and vegetables and they are produced by inadequate handling. Among these mishandlings are impacts and compressions that occur in the harvesting during the selection (with or without machinery), transportation and commercialization. In some cases, it is a summation of damages that accumulate since the harvest [4].

This work was developed with the intention to contribute to diminish fruit and vegetable losses. The proposed work started with the development of sphere-shaped load cells to quantify the compression forces and impacts suffered by fruits. To do this, corded instrumented spheres were previously developed [5] and their evaluation resulted as a base to the development of a wireless instrumented sphere presented in this paper.

II. Background

Concerning the use of portable instruments for the detection of impacts during the post harvest processes of fruits they can be divided it into two distinct categories: first, instruments capable of detecting accelerations and second, instruments capable of detecting compressions [2]. These compression sensors are also able to detect impacts if their frequency response is large enough to do that. The instruments for sensing accelerations are utilized to quantify the impacts suffered by fruits during selection and transportation. The most widely used instruments for impacts sensing is the Impact Recording Device (IRD), developed by the University of Michigan [7] and presently commercialized by Techmark, INC. This instrument can capture the three axes acceleration, with a 500g's (500 times the gravity acceleration) for each axis and is usually utilized to collect the data along the fruit and vegetable selection process. A company called Sensor Wireless [8] produces another commercially available equipment for impact analysis performing the real time data transmission by radio frequency to a PDA (Personal Data Assistant). In this case, the memory to store the acquired data is in the PDA. These equipments are able to detect impacts, working only dynamically. In order to capture compression forces, the second type of instruments are needed. Bollen *et al*. [9] developed an instrument to be used as a pseudofruit to sense compression forces, which basically consists of an instrumented load cell able to capture on one axis compressions and impacts. Concerning strain gauge load cells, there are many types and forms including shear beams, canister, ring and button for sensing compression forces, binary or other mechanical stress for use in different applications. For multidimensional force analysis there are some commercial load cells that are able to capture the forces along the axes utilizing a central rod that is instrumented with strain gauges placed in different positions [6]. These transducers usually measure forces in one axis and the moment in another axis. Others are able to measure three axes compression forces, but referenced only to one point. If only one axis of compression is necessary, a simple load cell like a shear beam could perform the job, but if two or three independent axes are necessary, a combination of load cells need to be used.

III. METHODOLOGY

To start the development of the wireless instrumented sphere for sensing forces in three dimensions, two corded prototypes were previously developed [5] and validated in case studies of measuring compression forces undergone by fruits in several different experiments. The developed devices have 55 and 80 mm of diameter each and proved that fruits face damages caused by strong compressions and impacts during the selection, packing and transportation. In order to ease the task of transferring sampled data from the pseudofruit to a computer for executing data processing and visualization, a wireless instrumented sphere was then developed. This section describes the data logger that was developed which includes two extra sensors (temperature and humidity) in order to perform storage and long-term transportation experiments.

The hardware was developed keeping in mind low power requirements. Two possible data transfer (USB port or RF) and an internal memory to store the acquired data were included. Fig. 1 describes the block diagram of developed hardware. The chosen microcontroller is a low power device and has features like analog and digital inputs, internal Flash memory, USB transceiver and I^2C and SPI buses. An external Flash memory with a 128 MB x 8 bits capacity was utilized for the storage of sampled data.

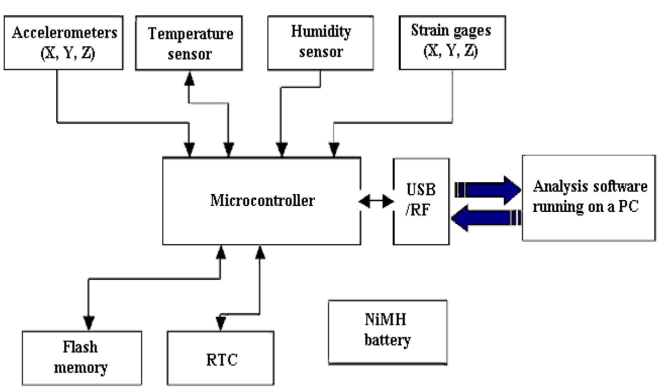

Figure 1. Block diagram of the proposed hardware

The data block size to be stored in the Flash memory is variable, according to the parameters chosen in the software being at least 63397 registers. The Flash memory is recorded as a circular buffer to maximize its lifetime. The developed data acquisition system produces a real time stamp for each triggered sample of compression or impact in order to correlate the stored data with the occurred event. A real time clock (RTC) performs this time stamping and communicates with the microcontroller through an I^2C interface running at 400 kHz.

Chosen accelerometers are single axis MEMS devices with a 250 g's positive and negative full scale based on a differential capacitive sensor. This extended scale range is necessary because fruits can suffer impacts of this magnitude [9]. The accelerometers were put in the center of the printed circuit board oriented according to the Cartesian axes. One of the sensors is placed in a dedicated to it small printed circuit board in order to stay vertically oriented.

The first sphere assembled was designed to have a final diameter of approximately 80 mm, which is considered adequate for experiments with fruits like apples and oranges. It is a device composed of three independent ring load cells assembled in a way that a compression force sensed by one cell would not affect the others making an individual measurement according to its corresponding axis. As the compression force values suffered by fruits were not exactly known by our horticultural department, it was arbitrarily established a 500 N full scale for the first prototype. It has been verified through further experiments [5] that the fruits suffered a maximum of 250 N in some cases.

The design of the ring load cells was done using mechanical stress calculation software and its thickness and width were chosen to withstand a charge of up to 500 N each. The software gives the maximum bending value that occurs in an object under certain compression or traction forces through finite element decomposition. Through the parameter variation of the project the correct dimensions of the aluminum rings were defined so that they could withstand the compression of up to 500 N, bending not more than 3 mm in total. This value was designed so that the rings would not touch each other, not affecting their measurements. The physical disposition of the rings (load cells) that make up the sphere is depicted in Figure 2. They are three rings, two concentric and one orthogonal in relation to the first two. The rings are held by rods, which are attached in the larger one and passes through the others, restricting the rotation movements among them. There are hubs like covers to form the volume of the sphere and transmit the compression force to each ring. Each pair of hubs is affixed in only one ring and the rod of the intermediate ring goes through the larger ring restricting even more the rotation among them. Colored surfaces were glued on the covers to absorb strong impacts thereby simulating a fruit surface besides correlating the correspondent axes to the software graphics (Figure 3). The choice of ring load cells was defined taking into account cost, simplicity and reliability requirements [10]. The simplicity comes from the fact that these rings are just machined aluminum rods. They are reliable load cells, light and easily manufactured.

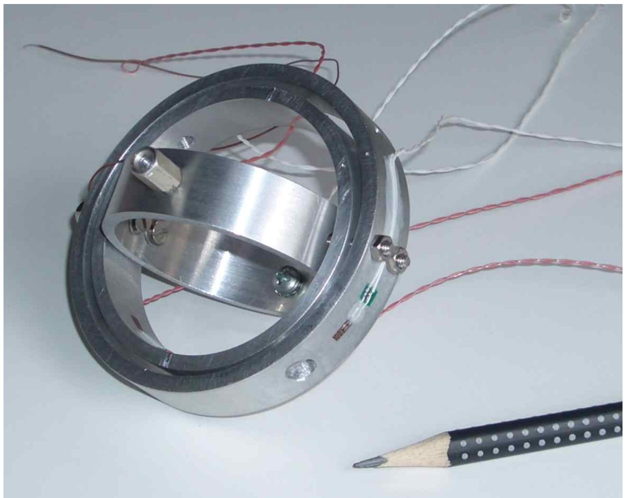

Figure 2. Mechanical structure of the 80 mm three-axis load cell during assembling. The three rings are shown without inside electronics and covers.

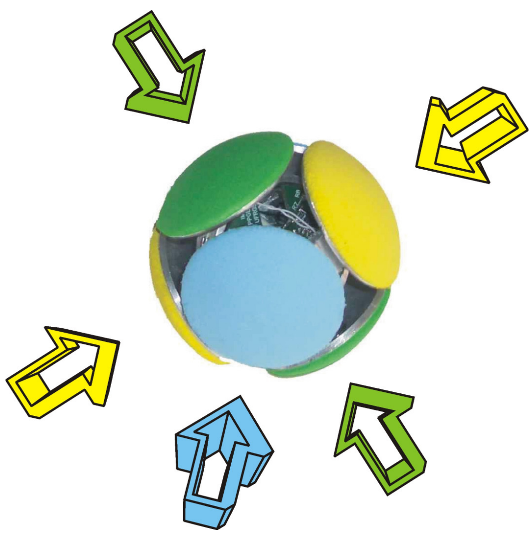

Figure 3. Finished prototype.

Signals obtained from the Wheatstone bridge of each ring load cell are amplified 620 times by an instrumentation amplifier. This initial gain value was estimated in terms of the maximum compression force (500N) chosen for each load cell. The estimation was done during an experimental procedure when rings were physically connected to a precalibrated load cell and compressed by a hydraulic press. With the correct amplification, the correspondent output voltage to each ring load cell is enough to be digitalized, exploring all the dynamic range of the ADC. The voltage excitation to the Wheatstone bridge is asymmetrical because the load cells only sense compression (not traction) so the bridge has always a positive unbalance. In order to minimize the natural offset presented by the ring load cells, one adjustable resistor was put in parallel with the positive arm of the Wheatstone bridge. The remaining offset was suppressed subtracting the extra value by software. This approach permits corrections during the use of the sphere because the offset changes every time the sphere is repositioned (due to the sphere's weight). To keep the bridge circuit's power consumption as low as possible, the excitation voltage was reduced to 1.2 V in comparison to previous developed prototypes [5] and the value of the fixed arm was increased to reduce the current. To correlate the output voltage of each ring load cell with kilograms-force of compression, fifty different compression force values were applied to the calibration set. The obtained characteristics were very linear, with a R^2 better than 99% for a straight line. This procedure was repeated after six months in order to evaluate the long-term stability of the prototypes. The calculated slopes, including the gain of instrumentation amplifiers showed a total error of 5% in the worst case. The nonlinearity obtained was 1.73% in the worst case. The accelerometers, temperature sensor and humidity sensor were calibrated with data supplied by their manufacturers. The calibration parameters were parameterized in the analysis software in order to change their value when needed.

The collected data can be sent by a radio frequency transceiver that operates at 2.4 GHz band, in ISM (*Industrial, Scientific and Medical*) frequency range. The RF module has a digital GFSK modulation that reduces the spread spectrum by shaping the digital pulses with a Gaussian filter. It supports channel hopping and transmits at 250kbps or 1Mbps rate. In the developed prototype, the maximum available USB current is limited by software in 200 mA, the necessary current value to recharge the internal NiMH batteries. Excluding the accelerometers and the humidity sensor, all devices used in the wireless instrumented spheres work at 3.3 V. Two NiMH batteries placed in series deliver the 2.4 V supply voltage. The choice for the NiMH batteries was due to its simple recharge circuitry when compared with lithium batteries. Lithium batteries have a better energy density being more adequate to portable systems but their recharge circuit is much more complex because of the risk of explosion and the deep discharge problem [11]. A non-isolated switched step-up regulator (Boost), elevates to 3.3 V with a 90% of efficiency and a low current, high efficiency charge pump device elevates to 5 V, the necessary voltage for the remaining circuits. Figure 4 depicts the final circuit boards of the prototype during tests (without load cells).

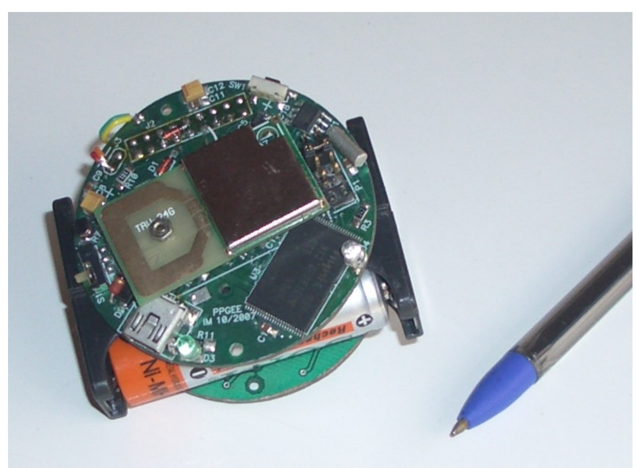

Figure 4. Data Logger without load cells.

With 2500 mA of capacity, the NiMH batteries promote a maximum autonomy of 25 hours for the prototype. The battery life time is estimated in the worst case, when the radio and the Flash memory are working all the time. These values are much larger if the measurements are done at intervals in a programmed cycle (selected through the software). A personal computer can then be interfaced with the prototype through a USB-RF adaptor for data collection, analysis and visualization using standard PC software. A graphical user interface was developed which displays the data in a graphic form with time stamp where the impact, compression, temperature and humidity may be analyzed (see Fig. 5). The occurrence of an impact trigger or a differential of compression results in the sending (or storage in the Flash memory) of a pre-determined number of samples. The host counts the number of received samples and it can, in the case of a loss in communication, request for the resending of the lost samples. Trigger and differential thresholds are parameterized and saved in the microcontroller's E^2PROM.

Figure 5: GUI of the software showing impacts, compressions, temperature and humidity recorded during instrumented sphere evaluation.

IV. EXPERIMENTAL VALIDATION

Several different experiments were performed in orange and apple packing houses and also at the horticultural laboratory. The experimental method basically consisted in positioning the instrumented sphere in place of one of the fruits during the selection, boxing and transport process. Some of the obtained results indicated strong compression forces on the fruits, especially those placed on the outside border of the boxes in the bottom layer of the pallets. In some cases compression forces of up to 19-kgf were determined. One of the most severe problems found, the box overfilling, occurs when one extra layer is placed over the last layer of fruits to obtain the required box weight. Another frequent problem is during pallet stacking when the placement of the boxes is not done in correct alignment with the previous ones where the border of the box can directly compress the fruits in another box (wooden orange boxes). Figure 6 shows one of the generated graphics in a box filling experiment. In this graph one can see the increase of the compression, which resulted from every additional box being stacked in the pallet. The experiment duration time was about four minutes and what appears to be noise in the measurements is actually impacts and the natural frequency of vibration that occurs by the addition of a new box in the stack.

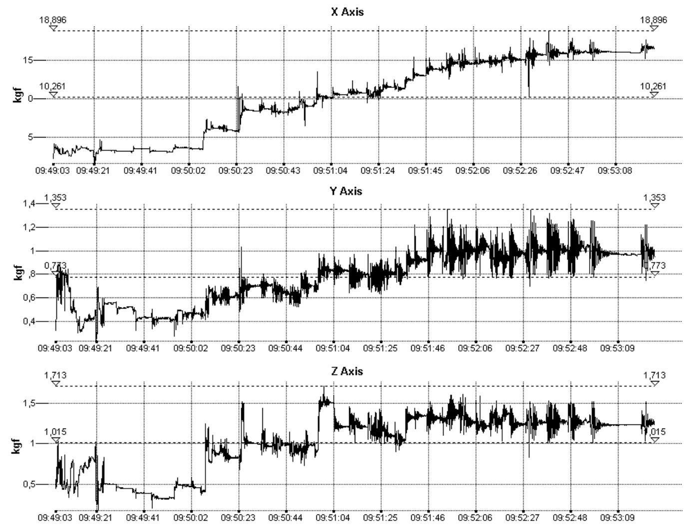

Figure 6. Graphics of the compression sensed by the instrumented sphere placed inside a fruit box.

As expected, all experiments indicated a stronger compression force in the vertical axis in relation to the horizontal. The instrumented sphere was placed in different positions and layers of the box during several experiments and, if the sphere is placed in a central position, it receives compression on the three axes. Therefore, a three axes device is sufficient to sense all the compression forces suffered by the fruits in cases like this.

During their usual selection process, oranges are transported by a conveyor belt and selected, depending on their sizes through previously calibrated openings. Two problems can occur in this case; the first one is the fall that the fruit suffers and its consequent impact at the bottom of the crate (in some cases the bottom is covered with sponges to absorb the impact) and the second is the impact suffered among the fruits that are falling and their impact with fruit that are already in the box. The instrumented sphere was placed substituting one of the fruits and compression and impact forces equivalent of up to 4 kgf were recorded.

Another case study was to evaluate the impact of motorized or manual lift trucks used in the pallet transportation up to and into the trucks or cold storage units. The experiments performed revealed that the wood that serves as a platform for the lifting suffer bending in some occasions, changing the direction of the compression forces inside of the fruit boxes making a kind of rearrangement of them. In some cases this rearrangement promoted strong lateral compression forces, up to 7 kgf and peaks of impact when the lifter releases the pallet. The lift truck operators usually release the pallet very quickly, producing strong compression peaks (more than 20 kgf in some cases) and vibrations. In other experiments, the wireless instrumented sphere suffered free falls recording impacts of 250 g's in average. This range of values is in accordance with previous works.

V. CONCLUSIONS

The main goal of this work was to develop a wireless portable instrumented sphere for the analysis of the impact and compression forces suffered by fruits during the post harvest process. It was also proposed that the portable instrumented system could serve as a common base for the development of other instruments and for that purpose it should contain modules such as USB and RF communications port and Flash memory to store the acquired data. The developed pseudofruit showed to be very useful, being used by researchers of the post harvest agricultural area department in our university. The three axes instrumented sphere gives more compression force data than the previous developed systems, which makes it more reliable, sensing all of the relevant forces. The impacts suffered by selected fruits which have already suffered the impact of the fall, can be quantified by the load cell, but not only with the spheres instrumented with accelerometers. The instrument also proved useful to explore long term transportations acquiring more data than those previously developed.

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REFERENCES

[1] A. H. OSTER , A. R. CORRENT, R. M. VALDEBENITO-SANHUEZA, R. J. BENDER, "Heat treatments to control white rot (Botryosphaeria dothidea) on `Fuji´ apples". Acta Horticulturae, Amsterdam, vol.712, p. 799-804, 2006.

[2] A.F. BOLLEN, "Technological innovations in sensors for assessment of postharvest mechanical handling systems", International Journal of Postharvest Technology and Innovation, Vol. 1, No. 1, 2006.

[3] R. M. V. SANHUEZA, "Podridões de maçãs frigorificadas. In: Maçã: pós-colheita". Ed.: Girardi, C. L. Bento Gonçalves (RS, Brazil): Embrapa Uva e Vinho. 2004. p.35-44. (Frutas do Brasil, 39).

[4] M. DESMET, V. VAN LINDEN, M. L. A. T. M. HERTOG, B. E. VERLINDEN, J. DE BAERDEMAKER, B. M. NICOLAI, "Instrumented sphere prediction of tomato stem-puncture injury. Postharvest Biology and Technology", Amsterdam, v.34, p.81-92, 2004.

[5] I. MÜLLER, R. M. BRITO, R. J. BENDER, "Instrumented Sphere for Compression Analysis", I2MTC 2008 - IEEE International Instrumentation and Measurement Technology Conference Victoria, Vancouver Island, Canada, May 12-15, 2008.

[6] J. L. SOMMERFIELD, A. R. MEYER, B. A. LARSON, D. J. OLSON, "Multi-axis load cell", U.S Patent Number 5,969,268, October, 1999.

[7] H. R. ZAPP, S. H. EHLERT, G. K. BROWN, P. R ARMSTRONG, S. S. SOBER, "Advanced Instrumentes Sphere (IS) for impact measurements", ASAE paper 89-6046, May 1990.

[8] SENSOR WIRELESS, Smart Spud [Online]. Available at: http://www.sensorwireless.com/smartspud.php.

[9] A.F. BOLLEN, E. J. TIMM, B. T. DE LA RUE, "Relation of individual forces on apples and bruising during orchard transport of bulk bins", Applied Engineering in Agriculture, Vol. 17,No. 2, pp.193–200, 2001.

[10] J. C. P. BECK, "Projeto, Construção e Análise de Células de Carga de Placa e de Anel", Master thesis, PPGEMM, Fedral University of Rio Grande do Sul, Brazil, 1987.

[11] MICROCHIP, "Selecting the Right Battery System For Cost-Sensitive Portable Applications While Maintaining Excellent Quality", Microchip Application Note AN1088, 2007, Available at http://www.eetasia.com/ART_8800477230_765245_AN_42b31fc0.HTM, Access in December, 2007.